

# OPTICAL CONTROL, DIAGNOSTIC AND POWER SUPPLY SYSTEM FOR A SOLID STATE INDUCTION MODULATOR

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**Abstract:** *A new high speed optical control, diagnostic and power supply system has been developed for a solid state induction modulator. The modulator consists of a large array of field effect transistors (FETs) that switch a high-voltage pulse across a tape-wound magnetic core. The FETs within the modulator are mounted on numerous circuit boards that are stacked in series for high-voltage operation. The new optical system overcomes the issue of voltage isolation by supplying each circuit board with optically coupled control power and high bandwidth signal information. An optical fiber is used to transmit laser light to a custom photovoltaic cell that provides dc power to the on-board control circuits. Optical fiber technology is again used to convey a pulse that contains detailed analog features to the FET gate controls. Diagnostic data and status information are also obtained from each board by similar optical methods.*

## I. INTRODUCTION

Three subsystems are being developed to produce an all optical modulator that uses optical fibers to achieve analog control, low-voltage power supply, and diagnostics. The modulator consists of a large array of field effect transistors (FETs) that switch a high-voltage pulse across a tape-wound magnetic core [1]. The FETs within the modulator are mounted on numerous circuit boards that are stacked in series for high-voltage operation. The new optical subsystems overcome the issue of voltage isolation and unwanted coupling capacitance by supplying each circuit board with optically coupled control power and high bandwidth signal information. Analog control of FETs can be used to regulate the modulator voltage and correct for pulse distortion due to loading of the modulator. An optically isolated power system that utilizes laser energy to power the electronic systems on each circuit board is used to eliminate ground loops and reduce coupling capacitances. A resistor in series with the source lead of the FETs is used for over-current protection and its small value makes it useful as a current viewing resistor (CVR). Converting the CVR signal to light supplies isolated diagnostic data and status information to the control system.

## II. ANALOG OPTICAL CONTROL

The solid state induction modulator requires an analog control subsystem to operate each FET in the linear region, which allows active voltage regulation of the modulator output pulse. This ability can be used to correct for pulse distortions due to loading of the modulator. The subsystem fans out a 10 MHz control signal to many receivers on voltage isolated printed circuit boards. Measurements of the switch modulator revealed that the series arrangement of the FET switch boards requires the control signals be timed so that the skew between any two receivers is less than 1 nanosecond. Timing skews greater than 1 nanosecond can place the entire switching voltage across one FET, causing it to exceed its voltage handling capabilities.

Conversion to a digital format for transmission over optical fiber was chosen for this application because the digital format is stable and less sensitive to changes in received optical power and thermal variations. Converting the digital signal to analog on the switch board was

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accomplished with a digital-to-analog-converter (DAC). To reproduce the input signal, the Nyquist Sampling Theorem requires a sampling rate of at least two times the highest analog frequency. Therefore, a 10 MHz input signal is reproduced without aliasing if sampled at a rate of more than 20 MHz.

Creating the digital bit stream was accomplished by converting the analog signal to digital with an analog-to-digital-converter (ADC). A vertical cavity surface emitting laser (VCSEL) array fiber optic transceiver [2], [3] link was used to transmit the parallel digital signals over optical fibers to a 400 MHz DAC. See Figure 1. The VCSEL link transmits 10 channels in parallel at up to 400 Mbps per channel for a total bit rate of 4 Gbps.

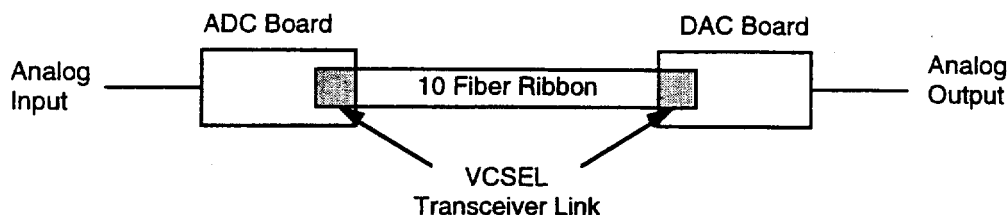


Fig. 1 -- Schematic of Analog Control Subsystem

Testing was performed with sampling rates of 1 MHz to 400 MHz. The DAC used was a 6 bit converter, two channels of the VCSEL link were used for transmitting the CLOCK and NOT-CLOCK signal and the other two channels were not used. Conversion of the analog signal to digital proved to be the more difficult problem. The system had oscillations with a period of 2 ns at sampling frequencies ( $f_s$ ) over 100 MHz. Due to improperly connected ground planes on the ADC board, we used ferrite beads to isolate the noisy digital ground plane from the clean analog ground. Sampling rates were reduced to 300 MHz for reliable performance.

A 15 MHz sine wave input signal and the output of the DAC are shown in Figure 2 for a sampling rate of 300 MHz. The resolution of this DAC is given by the vertical number of bits and the sampling rate. This DAC has a vertical resolution of 6 bits or 64 discrete levels. Dividing the output range into 64 levels gives 16 mV per level. A sampling rate of 300 MHz is a sample point every 3.3 ns, which gives 20 samples in one cycle of the 15 MHz sine wave. Looking closely at the waveforms in Figure 2, discrete levels or steps can be seen in both the input and the output waveforms. Filtering the output of DAC with a low pass filter or increasing the sampling rate will smooth out the steps.

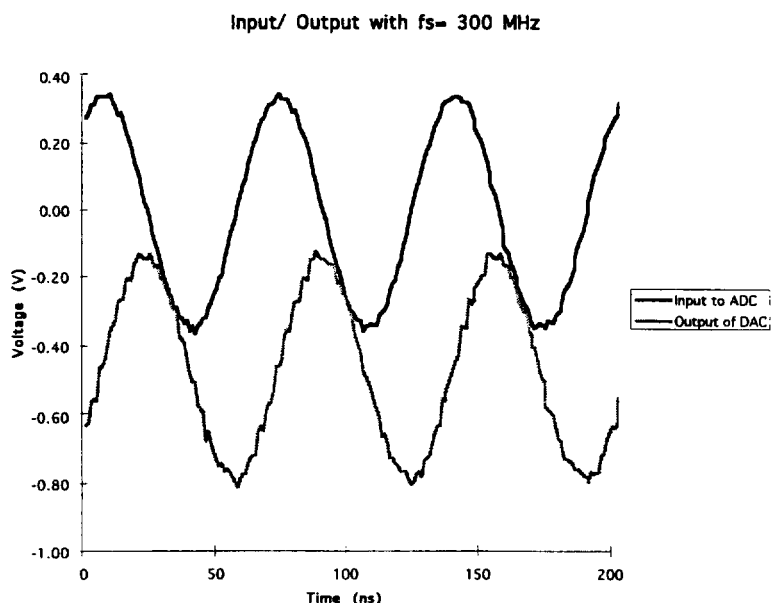


Fig. 2 -- Plot of DAC Input and Output

The DAC output is ideally 0 volts to -1 volts with discrete steps at every 15.6 mV, corresponding to the binary input incrementing by one least significant bit (LSB). After compensating for an offset error of 80 mV, the gain error (difference in slopes of the transfer functions) was measured at 1.4%, well below the specified value of 6.5% from the manufacturer. The gain error can be compensated by adjusting the reference current of the DAC. The offset error can be compensated by adjusting the bias level on the reference input on the DAC. Only the dynamic errors remain, which include the differential non-linearity error (DNL) and integral non-linearity error (INL). DNL is a measure of the difference between an actual step height and the ideal value of 1 LSB. INL is the accumulated DNL.

Measurements of analog bandwidth, risetime, falltime, spurious free dynamic range (SFDR), signal to noise ratio (SNR), gain error, DNL, INL, slew rate, input and output range were performed at a sampling rate of 300 MHz. For all measurements the DAC system exceeded the requirements for the Modulator as shown in Table 1. References on DAC testing can be found in [4] and [5].

Test	Result	Requirement	Units
Analog Bandwidth	64	> 10	MHz
Risetime	5.5	< 35	ns
Falltime	5.5	< 35	ns
SFDR	46.8	> 40	dB
SNR	60.3	> 50	dB
Gain Error	1.4	< 6.5	%F. S.
DNL	$\pm 0.3$	$\pm 0.5$	LSB
INL	$\pm 0.13$	$\pm 0.95$	LSB
Slew Rate	126	> 23	V/ $\mu$ s
Input Range	0 to -1000	0 to -1000	mV
Output Range	-12 to -983	0 to -1000	mV

Table 1 -- Table of Test Parameters, Results, and Requirements

### III. OPTICAL POWER CONVERTER SUBSYSTEM (OPC)

An optically isolated low-voltage power system for each circuit board is used to eliminate ground loops and reduce coupling capacitances. An optical fiber is used to convey laser light to a custom AlGaAs/GaAs solar cell [6] that converts the photonic energy into electrical power for the on-board control circuits. The OPC system has been used in high-voltage transmission line data acquisition systems [7] where isolation of 750 kV is required. The custom photovoltaic cell generates 0.2 W of peak electrical power from a 1.0 W laser at a load resistance of approximately 1 k $\Omega$  as shown in Figure 3.

Power Supplied vs. Load Resistance

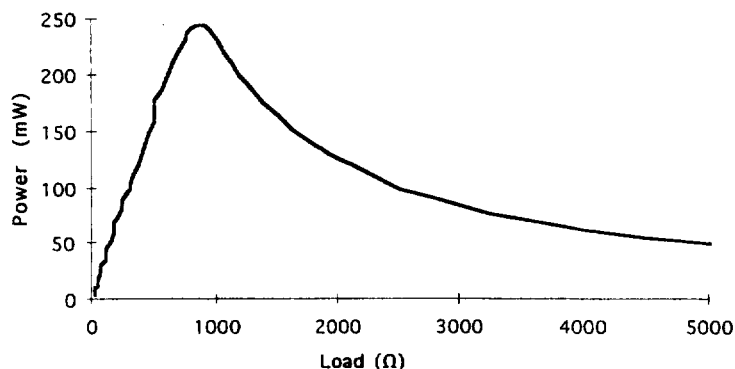


Fig. 3 -- Power Curve for OPC

The converter was coupled with a voltage regulator to regulate the output voltage to 15 V for the FET drivers and another regulator was used to step from 15 volts to 5 volts for the optical control receiver. Storage capacitors were used at each regulator stage and at the optical receiver to provide additional energy during the switching burst. The circuit was tested on a FET switch board that only switches the FETs ON or OFF, as the analog FET driver circuitry was not available at the time of testing for this paper. Daughter boards with the optical power converter, optical control receiver, and FET drivers were constructed and coupled into a switch board to replace an existing dc-dc converter, control receiver and FET drivers.

For comparison, the same bench setup was used to test both the modified and unmodified switch board. The OPC subsystem was tested for its ability to supply power for long pulses, narrow pulses at high pulse rate frequency and for variable pulse width and frequency. The subsystem was also tested for pulse width distortion, rise/fall time, jitter and droop of the FET gate pulse.

There was no significant difference between the OPC and the original dc-dc converter results for the dynamic tests. The FET switch card draws 4 mA of quiescent current from the OPC in standby mode and 10 mA during switching. The optical trigger receiver consumes most of the quiescent current at just over 3 mA. The FET drivers draw 12  $\mu$ A in standby. The short circuit current is rated at 20 mA. Initial charging of the storage capacitors takes 100 ms, allowing the subsystem to be turned on and ready to switch a burst within 500 ms of turning on the laser to conserve power while the modulator is not switching. The laser has the capability to be modulated from dc to 10 kHz. Large scale operation of this subsystem would allow low average power consumption while achieving high power switching. The laser was switched at a rate of 1 kHz and between 30% and 50% duty cycle to conserve power during standby. Modulating the laser saves laser lifetime and increases the reliability of the subsystem.

#### IV. OPTICAL DIAGNOSTIC

A resistor in series with the source lead of the FETs is used for over-current protection. This resistor has a small value and can be used as a current viewing resistor (CVR). Diagnostic data and status information from each array of FET circuit boards can be measured by converting the voltage across the CVR to light and transmitting through the high-voltage barrier to the control system [8]. A resistor-LED pair is placed in parallel with the CVR, as shown in Figure 4. A small amount of the current flowing through the CVR is diverted through the LED. The resistor in series limits the current through the LED. A plot of output optical power versus current is shown in Figure 5. Fitting a straight line to the data yields a slope of 5.8  $\mu$ W per mA and y-intercept of -13.1  $\mu$ W.

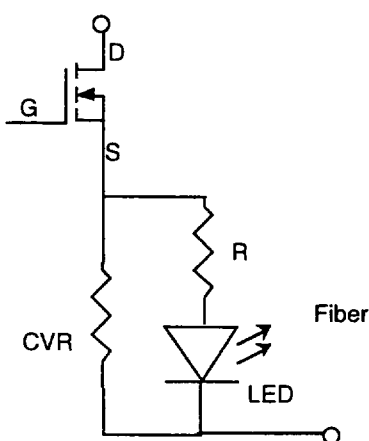


Fig. 4 -- Optical Diagnostic Circuit

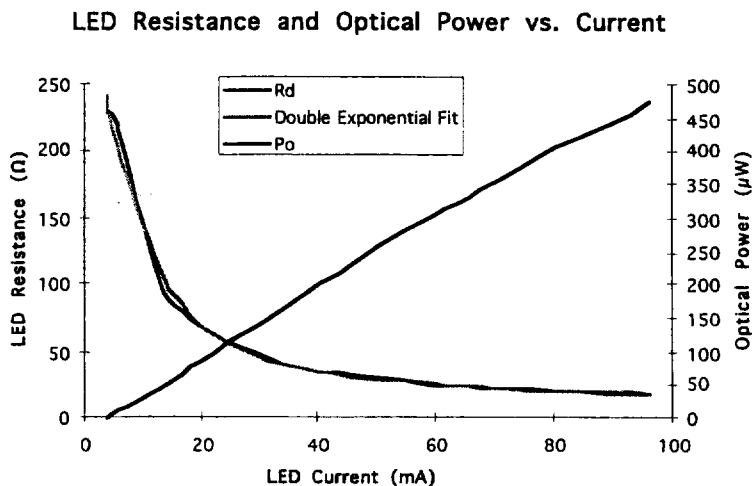


Fig. 5 -- LED Resistance and Power Curves

A double exponential curve fit of the diode resistance versus current curve (Figure 5) results in equation (1) for  $R_d$  for values of  $i_d$ .

$$R_d = k_0 + k_1 e^{-k_2(i_d)} + k_3 e^{-k_4(i_d)} \quad (1)$$

where:  $R_d$  is the diode resistance of the LED  
 $i_d$  is the current flowing through the LED  
 $k_n$  is the coefficients of the double exponential fit

A 40 mΩ resistor was used as the CVR and a 55 Ω resistor,  $R$ , was used to limit the current flowing through the LED. The current through the CVR can be calculated from the measured optical power using equation (2) and the straight line fit of  $i_d$  versus  $P_o$ .

$$I = \frac{i_d (R_d + R + \text{CVR})}{\text{CVR}} \quad (2)$$

where:  $R$  is the current limiting resistor  
CVR is the current viewing resistor 40 mΩ  
 $R_d$  from equation (1)

A 4 μF capacitor was charged to 500 V and switched across a short. A plot of the calculated CVR current from the optical power and the actual CVR current is shown in Figure 6. Lowering the value of  $R$  will divert more current to the LED and increase the sensitivity at lower CVR current.

#### Calculated and Measured Source Current

$V_{\text{charge}} = 500 \text{ V}$   $R_l = \text{Short}$

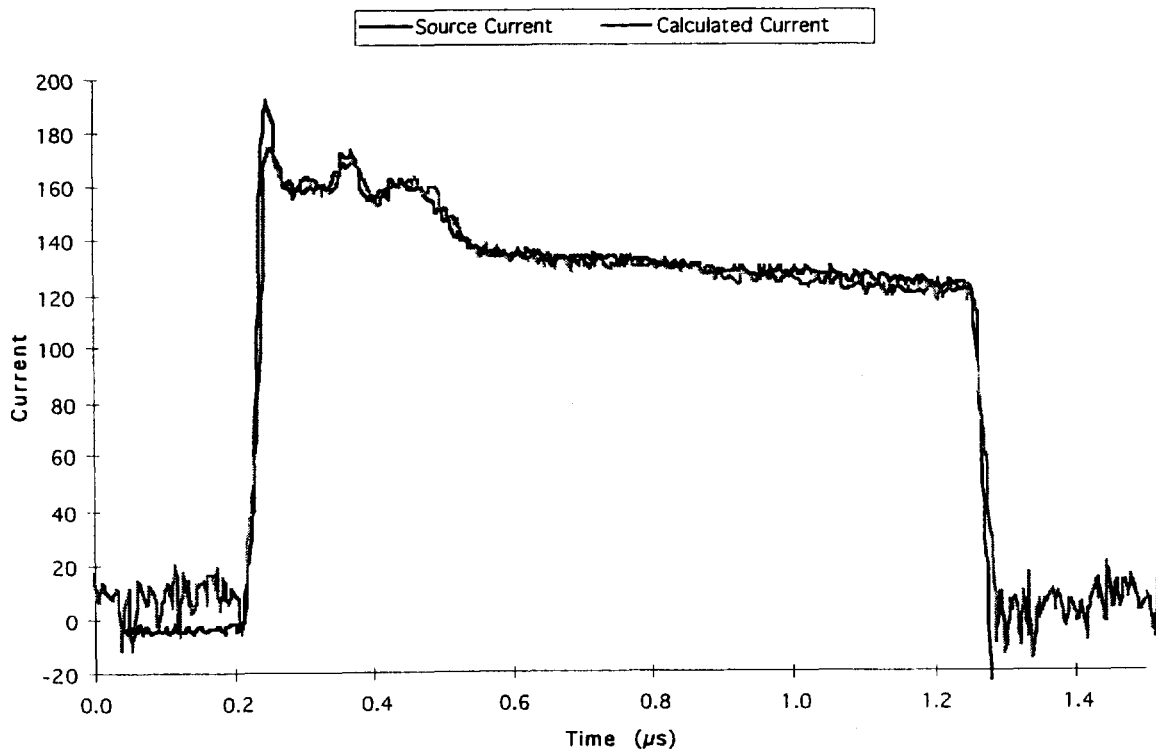


Fig. 6 -- Measured and Calculated Source Current

## V. CONCLUSION

VCSEL transceiver links and digital-to-analog converters can be used to transmit analog signals through optical fibers for high-voltage isolated systems. The creation of digital word waveform is easily accomplished with commercially available generators and transmission of this waveform through optical fiber is an effective medium. Conversion from a digital waveform can be accomplished with standard DACs. Future systems will utilize the digital output from an arbitrary waveform generator to avoid the process of converting from analog to digital by starting in the digital domain.

A method of supplying electrical power to high-voltage isolated systems utilizing laser energy delivered to a photovoltaic cell via optical fiber has been demonstrated. The system has been designed to allow conservation of energy and laser lifetime by switching the laser on just prior to triggering the modulator, then switching off the laser. Further conservation can be accomplished by modulating the laser during the operation of the solid state induction modulator.

Diagnostic signals can be transmitted through a high-voltage isolation barrier with optical fibers. Tapping the current flowing through the source lead of the FET with a CVR for the drive current of a LED is used for a voltage isolated diagnostic of the current switched by the FET.

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